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FTD-ID(RS)T-0385-90

FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

THERMOIONIC CONVERTER FOR SPACE REACTOR

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HUMAN TRANSLATION

FTD-ID(RS)T-0385-90 4 May 1990

MICROFICHE NR: FTD-90-C-000545

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English pages: 10

Source: He Ke Xue Yu Gong Cheng, Vol. 4, Nr. 3,
September 1984, pp. 227-232

Country of origin: China
Translated by: Leo Kanner Associates
F33657-88-D-2188
Requester: FTD/TTTDP/Capt Michael Mickenberg
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THERMOIONIC CONVERTER FOR SPACE REACTOR

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Manuscript received 27 July 1982

ABSTRACT

Thermionic converters offer many advantages for use as space reactors. Over the last several years, we have carried out six experiments, of which four were in-pile experiments and two out-pile experiments. Of the four in-pile experiments, three involved the use of three converters linked in series. The results show that at the maximum power density of $W=2.4$ W/cm², the electrode efficiency η was 4.2% and the emitting electrode temperature T_E was 1460° C. For the fourth in-pile experiment, with a single-unit thermoionic converter, $W=5.6$ W/cm², $\eta=8\%$, and $T_E=1540°$ C. In two of the out-pile experiments. when T_E was 1600°, the maximum power density $W=7.8$ W/cm², and the electrode efficiency η =12.7%.

1. FORWARD

The use of nuclear reactors as the power source for an electrical system in space is one of the important developmental projects under consideration today. For a time extending relatively long into the future, according to most opinions on potential power requirements, the choice of a thermionic converter to implement thermoelectric conversion has many advantages [4, 5]. The thermionic converter not only has a relatively high potential in power density and efficiency, but also has no moving mechanisms, and consequently has a relatively high system reliability. The thermionic converter has a very high waste heat discharge and diffusion temperature; in this way it is possible to reduce greatly the weight of heat radiators, which normally represent over half of the system's weight. In foreign countries large scale research on this subject began early [1-9].

2. THE THERMIONIC CONVERTER: BASIC PRINCIPLES AND EXPERIMENTS

The thermionic converter is in fact a kind of diode filled with cesium steam. For an in-pile thermionic converter, the reactor fuel element is the emitting electrode (the negative electrode); it is normally heated to 1,400° C and above, and on its surface hot electron emission occurs. The emitting electrode's outer concentric sleeve has a collecting electrode (the positive electrode). The gap between the two electrodes is normally 0.15-0.50 mm, ensured by a seal and insulation. In order to decrease the electrode surface work function and the effect of the space charge, the area between the electrodes is filled with cesium steam, so that the converter has a relatively high power density and efficiency. The output power density (W) and efficiency (η) of the converter, which is normally in electric arc condition, are respectively:

$$W = J \cdot V$$

in which the current density $J = AT_E^2 \exp\left(\frac{-\phi_E e}{KT_E}\right) - AT_c^2 \exp\left(\frac{-V_B e}{KT_C}\right)$ and the voltage $V = \phi_E - V_B$.

$$\eta \doteq \frac{0.82(\phi_E - V_B)J}{J\left(\phi_E + 2\frac{KT_E}{e}\right) + 10^{-12}T_E^4}$$

Here, K is the Boltzmann constant, ϕ_E is the emitting electrode work function, e is the electron charge, and T_E and T_C are respectively the temperatures of the emitting and collecting electrode. A is the Richardson constant, and V_B is the potential barrier index ($V_B = \phi_C + V_D$, in which V_D is the electrode space potential energy loss).

The goals of the thermionic converter experimentation are: 1) To develop a reliably working emitting electrode that can tolerate the high temperatures conditions of the converter. 2) To study and improve the electrode surface and its space conditions, in order to gain experience in raising the output electrical power density and efficiency. 3) To study and measure the parameters of the converters that have been developed and their interrelationship.

Table. 1. Results of the experiments.

	(3) 编号	(4) 试验目的	(5) 发射极形式及装置结构	(6) 发射极表面材料 / (7) 收集极表面材料	(8) 发射极温度 (°C)	(9) 输出电流密度 (A/cm²)	(10) 输出电功率密度 (W/cm²)	(11) 效率 (%)	(12) 运行时间 (h)	(13) 试验终止原因
堆内试验 (1)	DN3-1	(a) 串联特性	(d) A 型发射极三节串联	W/Nb	1650	1.7	1.0	1.3	250	(h) 焊缝开裂 [10]
	DN3-2	(b) 改进转换器串联特性	(e) B 型发射极三节串联	W/Ni	1460	5.3	2.4	4.2	170	(i) 性能下降 [11]
	DN3-3	(b) 改进转换器串联特性	(e) B 型发射极三节串联	W/Nb	1560	4.0	1.8	~ 4	220	(j) 发射极破损 [11]
	DN1-4	(c) 单节特性	(f) B 型发射极单节	W/Ni	1540	10.5	5.6	8	>270	(i) 性能下降 [12]
堆外试验 (2)	DW-1	(c) 单节特性	(g) 空心圆柱形发射极	W/Ni	1600	11.2	7.8	12.7	~200	(h) 焊缝开裂 [13]
	DW-2	(c) 单节特性	(g) 空心圆柱形发射极	W/Ni	1600	7.1	6.0	11.5	—	(h) 焊缝开裂 [13]

Key, row and column headings: (1) In-pile experiments; (2) Out-pile experiments; (3) Serial number; (4) Goal of experiment; (5) Type and installation structure of emitting electrode; (6) Emitting electrode surface material; (7) Collecting electrode surface material; (8) Emitting electrode temperature; (9) Output current density; (10) Output power density; (11) Efficiency; (12) Operation time; (13) Reason for terminating experiment.

Key, tabulated data: (a) Serial characteristics; (b) Improve converter serial characteristics; (c) Single unit characteristics; (d) Type A emitting electrode, series of three; (e) Type B emitting electrode, series of three; (f) B type emitting electrode, single unit; (g) Hollow core cylindrical emitting electrode; (h) Split in welded seam; (i) Reduction of performance; (j) Damage to emitting electrode.

See Fig. 1 for the earliest experiment's three-unit series converter in-pile installation. Table 1 presents the experimental conditions for the four in-pile installations and the two out-pile installations.

For the out-pile experiments, we used electron bombardment for heating. For the in-pile experiments, we used 20% ^{235}U UO_2 fuel for fission heating, and the experiment was undertaken on a swimming-pool style experimental reactor. For measuring the characteristics of electric power output, we used a special manually/electrically driven rheostat and a specially constructed triode dynamic state measurement installation.

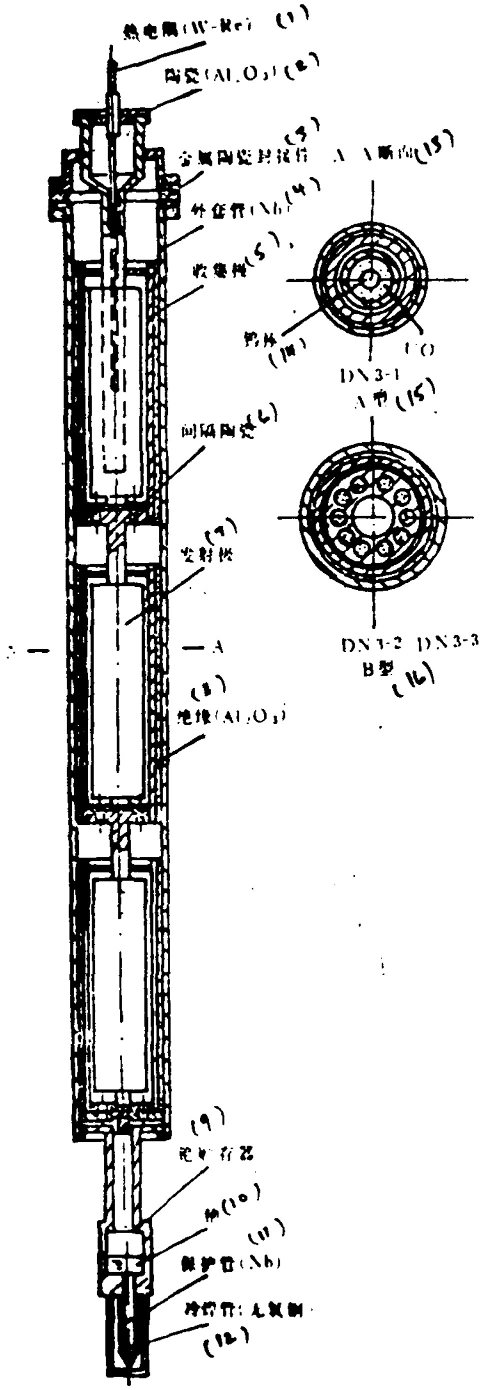

Fig. 1. Thermionic converter in-pile experimental installation. Key is at right of figure.

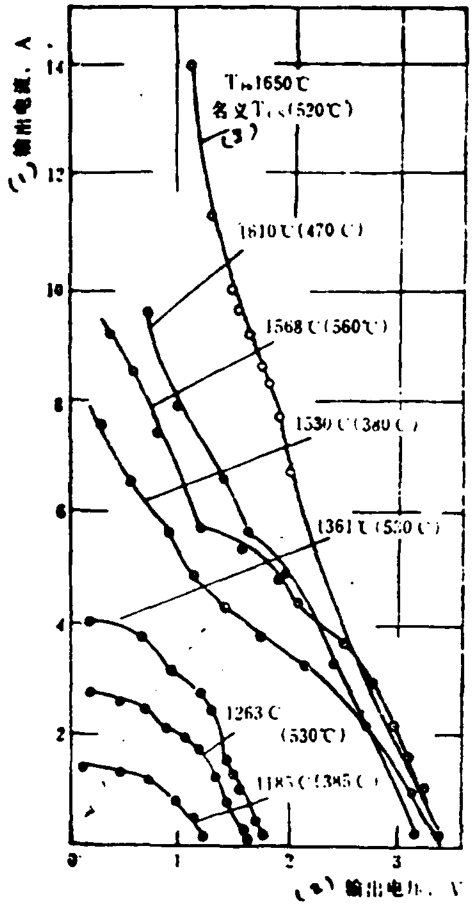

Fig. 2. Characteristics of DN3-1 volt and amp output. Key: (1) Output current; (2) Output voltage; (3) Nominal.

Key for Fig. 1: (1) Thermoelement; (2) Ceramic; (3) Metallic/ceramic seal interface element; (4) Outer tube; (5) Collecting electrode; (6) Gap ceramic; (7) Emitting electrode; (8) Insulation; (9) Cesium reservoir; (10) Cesium; (11) Protective tube; (12) Cold weld tube, no copper oxide; (13) Section A-A; (14) Tungsten body; (15) Type A; (16) Type B.

3. RESULTS OF EXPERIMENTS

Table 1 shows the maximum output conditions attained from the experiments within the range of adjustments made to the temperature of the collecting electrode and the cesium vapor.

3.1. The Electrical Output in Terms of Volts and Amps

In each experiment, we undertook measurement of the output voltage and output current characteristics (that is, the volt/amp characteristics) under conditions of different working parameters. Figure 2 shows the measured results for DN3-1. During the continuous changes in voltage and current, there often appear turning points in the curve, and near these turning points we occasionally measured locally irreversible regions (Fig. 3).

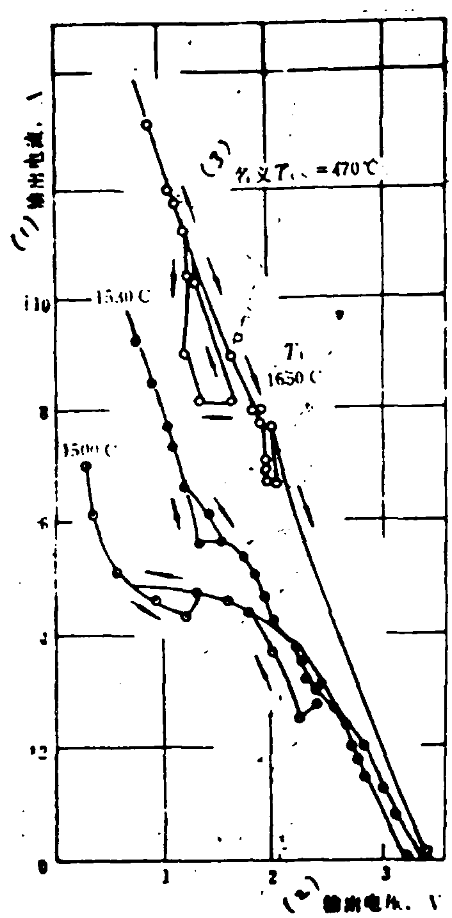

Fig. 3. Abnormal volt/amp characteristics that appeared in DN3-1. Key: (1) Output current; (2) Output voltage; (3) Nominal.

3.2. Effect of Electrode Temperature on Power Output

The temperature of the emitting electrode has an important effect on the output power and efficiency. For the in-pile three-unit serial converter, the graphs obtained by measurement are as shown in Fig. 4. The output power forms an S-shape graph with the input heat load or emitting electrode temperature. An S-shape graph not only appears for experiment DN3-1, but also shows clearly in experiments DN3-2 and DN3-3.

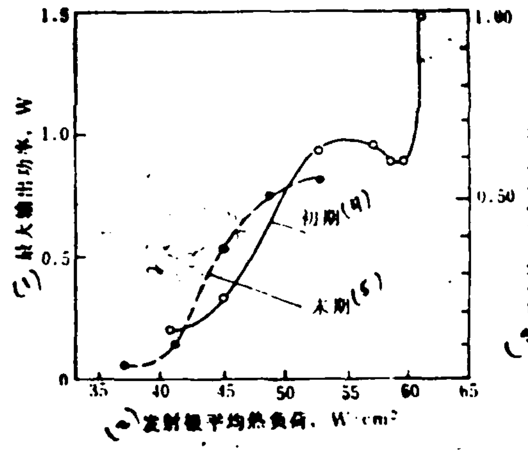

Fig. 4. Relation between emitting electrode average thermal load and maximum output power. Key: (1) Maximum output power; (2) Average heat load of emitting electrode; (3) Maximum power output density; (4) Initial period; (5) End period.

When the collecting electrode's temperature is less than 700° C, the effect on output power and efficiency is not striking.

3.3. Effect of Cesium Temperature

The cesium vapor pressure between the electrodes is determined by the temperature of the liquid state cesium, and adjustments are undertaken via the temperature of the external cesium reservoir (i.e., the nominal cesium temperature) . Regarding single-unit converters, if the nominal cesium temperature rises, there is a peak value in the corresponding output energy, and moreover, as the emitting electrode's temperature rises, the optimal nominal cesium temperature of the corresponding output power peak value increases. However, in the DN3-1 three-unit series converter experiment, the conditions shown in Fig. 5 occurred.

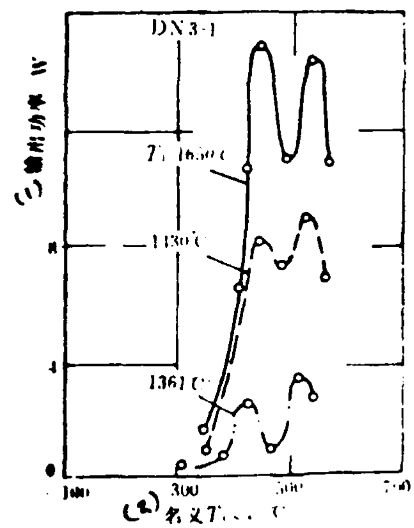

Fig. 5. Relation between nominal cesium temperature and output power. Key: (1) Output power; (2) Nominal T_{Cs}.

4. DISCUSSION

On the basis of the relational patterns discussed above and the experimental results obtained, it can be said that the size of the converter's power output is intimately related to the emitting electrode's temperature and to the cesium temperature. In in-pile experiments, owing to limitations in the structural design, and because the heat transference of the emitting electrode and the collecting electrode serial conductor and the axial direction distribution of particle flux within the reactor are not evenly distributed, it is inevitable that an unevenness be produced for the surface temperature of the emitting electrode in the single unit or between each of the several units. It is necessary to point out for Table 1 and the results of the experiments discussed above that the temperatures of the emitting electrode are all indicated as peak value temperatures in the experimental converter, and that they are limited by the maximum permissible temperature for the emitting electrode material. The unevenness of the temperature field of the converter, as well as the cesium vapor pressure, are controlled by the common cesium temperature, giving rise to the complexity of the output power characteristics in multiple-unit serial converters and lowering the power and efficiency [14].

In the serial converter subassemblies with uneven axial temperature fields, the single-unit converter's emitting electrode temperature is $\{T_{Ei}\}$; under conditions of the same output current, the serial subassembly output voltage is:

$$V = \sum_{i=1}^{n} V_i \ (T_{Ei}, \ T_{cs} \cdots\cdots)$$

n is the number of single-unit converters linked in series. For this reason, the output characteristics of the serial converter should be, under the same electrical current conditions, an iterative increase of the single-unit converter output voltage. In the experiments, dynamic measurement of single-unit converter output volt/amp characteristics has shown that within a rather large range of emitter electrode temperatures, there exist two working states, the "arc forming" and the "arc destroying" states. Furthermore, near the mutually filtered voltage and current parameters, there is formed an irreversible and unstable volt/amp region. During the process of the single-unit volt/amp characteristic iterative increase that we have discussed, because of the unevenness of the temperature field, these unstable conversion regions are not coincident, but the turning points in Fig. 3 and Fig. 4 often appear, as well as a number of unstable regions.

The "S" variation graph (Fig. 4) for the emitting electrode temperature and the output power is also caused because of this kind of single-unit power iterative increase under identical current conditions, as is the inner electrical power non-linear loss.

In a serial converter, because the emission temperature of every unit converter is not the same, the required optimal cesium temperature is not the same. However, because of structural design limitations, the serial converter normally uses a common cesium reservoir to supply cesium vapor for each single-unit converter; for this reason, under indentical cesium temperature conditions, each single-unit converter is not put in a cesium temperature state which is optimal for the output of power. This not only further lowers the output power of the serial converter, but also produces the violently undulating effect shown in Fig. 5 that the changes in cesium temperature have on the optimal power output. Experimentation shows that as the maximum output temperature of the emitting electrode rises, the cesium temperature has a strong effect on the output power.

5. BRIEF SUMMARY

1. In the initial thermionic converter experiments, the single-unit out-pile experiment's thermoelectric efficiency already had reached 12.7%, with an power density of 7.8 W/cm^2. Because of structural design limitations on the in-pile experimental converters and uneven electrode temperature fields, the electrical output capacity decreased severely for the in-pile experiments under multiple-unit series conditions (see Table 2). The design was improved, causing the unevenness of converter working temperature field to decrease; this is of great significance for raising the current output capabilities of multiple-unit series converters.

2. Regarding the in-pile multiple-unit series converters, the electrode temperature field is not even, complicating the output characteristics; furthermore, during the process of the continuous rise of the cesium temperature, the output power shows multiple peak values.

Table 2. Comparison of optimum conditions
for in-pile and out-pile converter experiments.

发射极温度（不均匀峰值）T_E，°C (1)		1460	1560	1600
堆内三节 (2) 串联转换器	相对功率密度 $\bar{W}$ (4)	0.98	0.42	—
	相对效率 $\bar{\eta}$ (5)	0.70	0.43	—
堆内单节 (3) 转换器	相对功率密度 $\bar{W}$ (4)	1.87	1.36	0.77
	相对效率 $\bar{\eta}$ (5)	1.28	0.88	0.68

Key: (1) Emitting electrode temperature (uneven peak values) T_E, °C; (2) In-pile three-unit series converter; (3) In-pile single-unit converter; (4) Relative power density; (5) Relative efficiency.

3. Based on our experiment's initially developed thermionic converter and on the experimental results, we further improved the surface material and the technology of the emitting electrode and the collecting electrode, and reduced the power loss between electrodes; this has great potential for further research to raise the converter's output energy density and efficiency, particularly in the case of the V_E value, which for out-pile experiments was 2.13 V and for in-pile single-unit experiments was 2.19 V. If on this basis we make improvements in material and techniques, and V_E drops to 1.5 V, the power density can reach 8 W/cm^2 and the efficiency can reach about 20%.

4. In future experiments to study the usable life of the apparatus, it will be necessary to improve further the welding technology of the emitting electrode and the sealing technology for the metal/ceramic seal interface. In the above experiments and other special experiments [15] it has been shown that the use of Ag-Cu fiber material for the metal/ceramic seal interface, at the working temperatures of the converter, is corroded by the cesium within 250 hours, and loses its sealing function.

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